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VLBI and GNSS Frequency Link Instabilities during CONT Campaigns

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Abstract

We present frequency link instabilities derived from the analysis of VLBI and GNSS data observed during the CONT08 and CONT11 campaigns. The majority of the stations involved in these two CONT campaigns did connect their VLBI and GNSS equipment to the same hydrogen masers used as the common local frequency standard. This allows comparison of the frequency instability on individual baselines from both VLBI and GNSS data analysis. This was done by analyzing the relative clock parameters. For VLBI the relative clock parameters with respect to a reference clock in the VLBI networks were derived from standard VLBI data analysis. For GNSS the relative clock parameters were calculated by differencing station clock parameters derived from GNSS precise point positioning analyses. The Overlapping Allan Deviation analysis was then applied to determine the frequency instability between pairs of stations. The most stable baseline for both CONT08 and CONT11 is the baseline between Onsala and Wettzell with instabilities of about 1.6e-15 at time intervals of one day. Frequency estimates from VLBI and GNSS analysis agree to a level of better than 5e-16 for the two week long data set with an RMS of less than 100 ps.

1. Introduction

National Metrological Institutes (NMI) often have the task of realizing UTC. Usually this is achieved by operating ensembles of frequency standards such as cesium clocks, cesium fountains, hydrogen masers, etc. The recommendation is to realize UTC with an accuracy of better than ± 100 ns. For this purpose the NMIs need to compare their clocks repeatedly with other NMIs. Several redundant techniques are used for these comparisons, e.g., two-way satellite time and frequency transfer (TWSTFT), various GNSS-based techniques, etc. [5].

In this context the use of VLBI has been discussed quite a long time ago. In the 1970s and 1980s there was quite a lot of interest in using VLBI for this purpose. In the 1990s the focus moved more to GNSS-methods, while in recent years there has been increased interest in VLBI from the metrology community. A short summary of important references is given in [3].

The more recent results indicate that VLBI reaches the same level of accuracy for frequency transfer as GNSS-based approaches [3]. Thus VLBI has a potential to serve as an alternative for frequency transfer that is independent from any satellite operator and potential problems due to natural or man-made disturbances of satellite operations.

In the following we present results from frequency link instability studies using VLBI and GNSS data observed during the two continuous campaigns CONT08 and CONT11.

2. CONT08 and CONT11

The continuous VLBI campaigns CONT08 and CONT11 were observed during August 12-31, 2008, and September 15-29, 2011, involving 11 and 13 IVS stations, respectively. The involved stations also operate co-located GNSS stations that are part of the IGS network. For the CONT08 campaign, 7 out of the 11 and for the CONT11 campaign 11 out of the 13 stations used the same hydrogen maser for the local frequency distribution for both the VLBI and the GNSS equipment. Table 1 gives an overview of the IVS and IGS stations involved.

Table 1. IVS and IGS stations contributing to CONT08 and CONT11.

IVS	IGS	Common frequency standard for VLBI and GNSS
Participating in both CONT08 and CONT11		
HARTRAO	HRAO	Yes: EFOS-C 28
KOKEE	KOKB	Yes: Sigma Tau
NYALES20	NYAL	Yes: APL No 2
ONSALA60	ONSA	Yes: CH1-75A
WESTFORD	WES2	Yes: APL No 3, Yes: APL No 4
WETTZELL	WTZR	Yes: EFOS 18
TIGOCONC	CONZ	Yes: EFOS 24 (CONT08), Yes: EFOS 20 (CONT11)
TSUKUB32	TSKB	No: Anritsu RH401A (Cont08), Yes: Anritsu SA0D05A (CONT11)
ZELENCHK	ZELE	No: CH1-80 (CONT08), Yes: VCH-1003A and CH1-80M (CONT11)
Participating only in CONT08		
MEDICINA	MEDI	Yes: EFOS 4
SVETLOE	SVTL	No: CH1-80
Participating only in CONT11		
BADARY	BADG	Yes: CH1-80M
FORTLEZA	BRFT	No: Sigma Tau
HOBART12	HOBA	No: VCH-1005A
YEBES40M	YEBE	Yes: EFOS iMaser S/N 66

3. VLBI and GNSS Data Analysis

The VLBI data of both CONT campaigns were analyzed with the VLBI data analysis software Calc/Solve [1]. The setup was a standard network solution using the 15 days of each CONT campaign independently. Radio source coordinates were fixed to ICRF2, while station coordinates were kept fixed on VTRF2008a values. However, for CONT11 the station coordinates of Tigo Concepción and Tsukuba were estimated on a daily basis since these two stations were affected by earthquakes in early 2010 and early 2011, respectively. Earth rotation and orientation parameters were estimated on a daily basis. Atmospheric parameters were estimated as piece-wise linear offsets for zenith wet delays every 20 minutes and horizontal gradients once a day. As constraints we used 50 ps/hour for the zenith wet delays, 0.5 mm for the gradient offset, and 2 mm/day for the gradient rate. One station clock was used as a reference clock, and clock parameters for all other stations were estimated as daily second order polynomials together with additional continuous spline corrections every 20 minutes. The clock constraints were 5e-14. The results of interest for the study of frequency link instability are the daily time series of relative clock parameters.

The GNSS data analysis was performed with the NRCAN-PPP software [2]. GPS data of the individual stations were analyzed with the precise point positioning strategy in a continuous mode, i.e. avoiding 24 hour batches. Final orbit products were used, and station positions were estimated on a daily basis. Zenith wet delays and horizontal gradients were estimated as random walk parameters. Clock parameters were estimated as a white noise parameter with 1 minute updates. The results of interest for the study of frequency link instability are the time series of clock parameters. Relative clock parameters with respect to the same reference station as in the VLBI case were calculated by differencing the time series of clock parameters.

4. Frequency Instability Analysis

In a first post-processing step so-called day boundary offsets had to be removed from the VLBI relative clock parameters in order to create continuous time series. These day boundary offsets are artifacts caused by the VLBI processing with the Solve software that is based on databases including 24 hours of data. Since one database at a time is analyzed, there is no continuity of the clock parameters at day boundaries. Small offsets occur that need to be removed. For the continuous GNSS-analysis such offsets do not occur.

In the next step quadratic clock models were fitted to the 15-day long continuous time series of relative clock parameters from VLBI and GPS. This was done since we compare the link instabilities of the two methods (VLBI vs. GPS) and not the clocks themselves. The assumption behind that is that the clocks are inherently stable during time intervals of up to one day and that the links are more noisy than the clocks. Figure 1 depicts examples for time series after removing quadratic clock models for the baseline Onsala-Wettzell for both VLBI (top left) and GPS (top right) for CONT11. These time series were the input to the Overlapping Allan Deviation (OADev) analysis to derive the frequency instability. Additionally, the time series were differenced (GPS-VLBI) and a linear fit to these differences was calculated. The tilt of the linear fit represents the difference between the frequency estimates of VLBI and GPS for every baseline, thus expressing the degree of agreement between the methods. An example is shown in the bottom graph in Figure 1.

Examples for the Overlapping Allan Deviation analyses are presented in Figure 2. Shown are the VLBI results for all CONT08 (left) and CONT11 (right) baselines. For the baseline providing the best results in both CONT campaigns, Onsala-Wettzell, the Overlapping Allan Deviation at one day is on the order of 1.6e-15 and better. Table 2 lists the results for both CONT campaigns.

5. Conclusions and Outlook

The analysis of CONT08 and CONT11 indicates that VLBI and GNSS perform equally for frequency comparisons. Overlapping Allan Deviations for one day on the order of 1.2e-15 and better can be achieved. VLBI and GPS derived frequency estimates agree in most cases with common clocks at a level of 5e-16, with residual phase differences on the order of 100 ps RMS. This makes VLBI an interesting alternative to the usual techniques applied for frequency transfer. With the upcoming VLBI2010 system [4], continuous time and frequency transfer with VLBI could thus become reality.

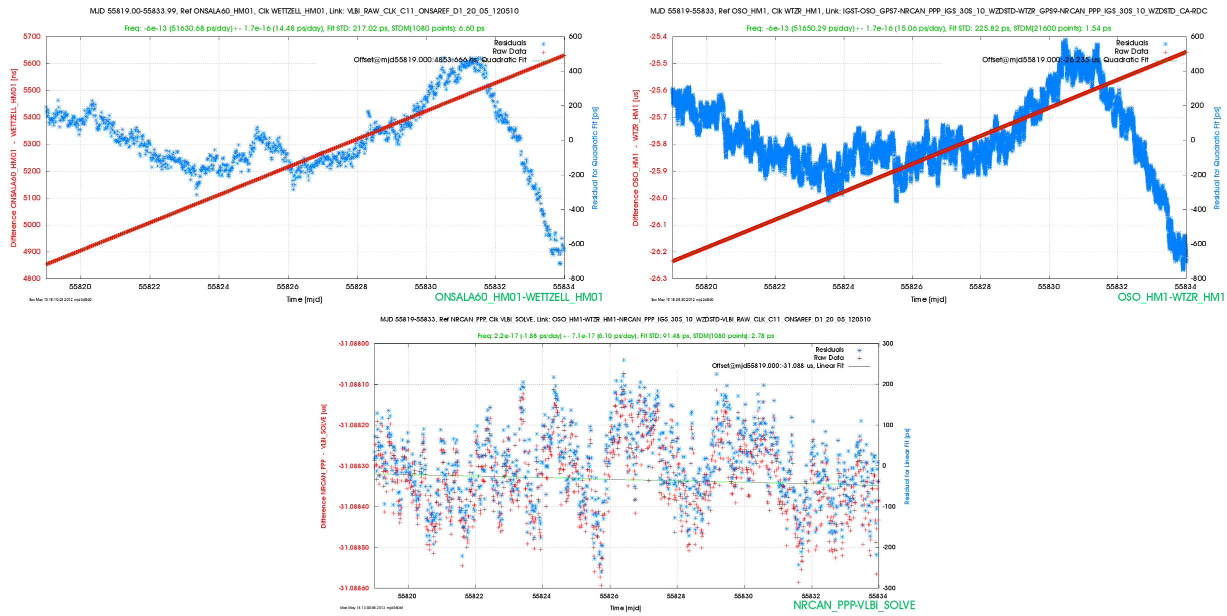

Figure 1. Top graphs: relative clock parameters on the baseline Onsala-Wettzell during CONT11 from VLBI (left) and GPS (right). Raw data are shown as red plus signs, while residuals after subtracting a quadratic clock model are shown as blue stars. Bottom graph: differences between the VLBI and GPS clock residuals in the two above graphs. The green straight line represents a linear fit to the differences (red plus signs), and its tilt represents the relative frequency trend between VLBI and GPS solutions.

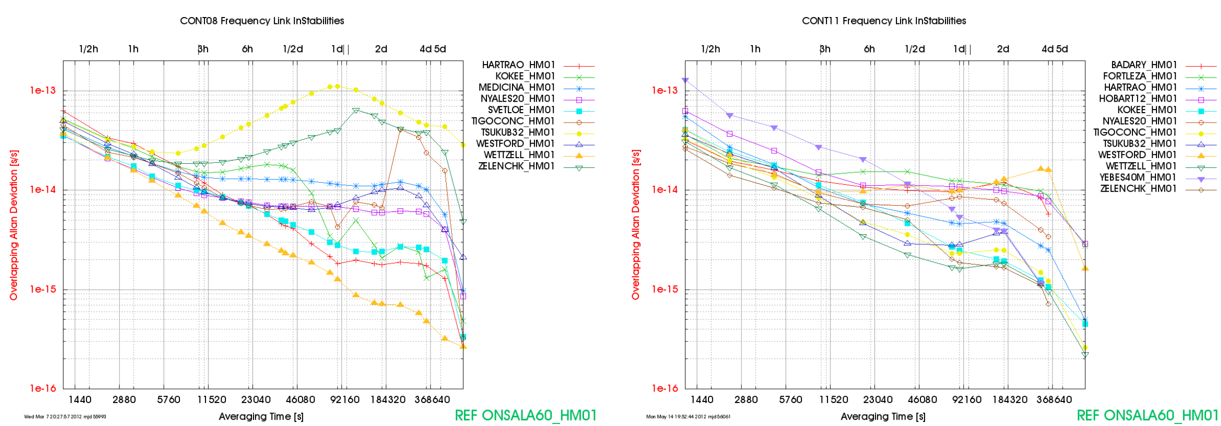

Figure 2. Frequency link instability for CONT08 (left plot) and CONT11 (right plot).

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Table 2. Frequency link performance for CONT08 and CONT11. Onsala is used as the reference clock. Shown are the Overlapping Allan Deviations (OADev) at one day for VLBI (V) and GPS (G), the relative frequency trend (Δf) for GPS-VLBI (G-V), and the root-mean-square (RMS) of the linear fit for GPS-VLBI.

Station	CONT08				CONT11			
	V	G	G-V		V	G	G-V	
	OADev @ 1 day		Δf	RMS	OADev @ 1 day		Δf	RMS
Participating in both CONT08 and CONT11								
HART	1.9e-15	8.5e-16	3.8e-17	260 ps	4.6e-15	4.9e-15	1.3e-15	337 ps
KOKE	3.0e-15	3.2e-15	7.4e-17	210 ps	2.5e-15	2.2e-15	1.2e-15	146 ps
NYAL	6.8e-15	6.5e-15	−4.5e-16	110 ps	8.6e-15	1.4e-14	−2.1e-16	645 ps
WEST	7.1e-15	8.4e-14	–	–	9.9e-15	9.6e-15	−2.6e-16	176 ps
WETT	1.2e-15	6.2e-16	4.8e-16	70 ps	1.6e-15	1.5e-15	−2.2e-17	92 ps
TIGO	4.3e-15	6.1e-09	–	–	2.3e-15	1.8e-15	−1.2e-15	176 ps
TSUK	1.2e-13	6.5e-14	–	–	2.0e-15	3.6e-13	−9.2e-16	183 ps
ZELE	4.0e-14	4.1e-10	–	–	1.8e-15	1.9e-15	1.7e-16	114 ps
Participating only in CONT08								
MEDI	1.2e-14	1.2e-14	1.2e-15	340 ps				
SVET	2.8e-12	1.1e-12	–	–				
Participating only in CONT11								
BADA					2.9e-14	1.9e-15	−1.1e-15	107 ps
FORT					1.2e-14	5.1e-14	2.4e-13	4.6 ns
HOBA					1.1e-14	5.6e-15	−5.9e-13	1.3 ns
YEBE					3.0e-14	3.6e-15	−9.3e-16	303 ps

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